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CP violation in B decays at the BABAR experiment

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Abstract

During the first year of data taking, the 1999-2000 run, the BaBar detector at the SLAC PEP-II asymmetric collider has collected an integrated luminosity of $20.7\,\mathrm{fb}^{-1}$ corresponding to 22.7 million $B\overline{B}$ pairs at the $\Upsilon(4S)$ resonance. Using this data, we present the measurement of $\sin 2\beta$ based on samples of $B^0 \to J/\psi\, K^0_S$, $B^0 \to \psi(2S) K^0_S$ and $B^0 \to J/\psi\, K^0_L$ decays. Our measured value is $\sin 2\beta = 0.34 \pm 0.20\,(\mathrm{stat}) \pm 0.05\,(\mathrm{syst})$. In addition we report on the measurement of branching fractions for exclusive B decays to charmonium final states, measurements of charged and neutral B meson lifetimes and also the $B^0\overline{B}^0$ oscillation frequency.

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1 Introduction

The *BaBar* experiment [1] is designed to allow detailed studies of *CP* violation in the B meson system. The main goal is to investigate whether *CP* violation can be fully explained within the Standard Model by the imaginary phase of the Cabibbo-Kobayashi-Maskawa matrix, or if other sources of *CP* violation should be considered [2]. To achieve this goal we need to over constrain the Unitarity Triangle by measuring the sides of the triangle using non-*CP* violating processes which give $|V_{ub}|$, $|V_{cb}|$, and $|V_{td}|$, while measuring the angles using *CP* violating processes [2]. The determination of the angles is achieved by studying time dependent asymmetries of the neutral B meson decays to *CP* eigenstates, f_{CP},

$$\begin{aligned} a_{f_{CP}}(t) &= \frac{\Gamma(B^0(t) \to f_{CP}) - \Gamma(\overline{B}^0(t) \to f_{CP})}{\Gamma(B^0(t) \to f_{CP}) + \Gamma(\overline{B}^0(t) \to f_{CP})} \\ &= \frac{(1-|\lambda|^2)\cos(\Delta m_d t) - 2\mathrm{Im}\lambda \sin(\Delta m_d t)}{1+|\lambda|^2}. \end{aligned} \tag{1}$$

For certain B^0 decays, where other types of *CP* violation are assumed negligible, this equation reduces to

$$a_{f_{CP}}(t) = -\mathrm{Im}(\lambda)\sin(\Delta m_d t), \tag{2}$$

where $\lambda \equiv \frac{q}{p}\frac{\bar{A}_{f_{CP}}}{A_{f_{CP}}}$. The complex parameters q and p are from B mixing, Δm_d is a measure of the $B^0\overline{B}^0$ oscillation frequency, and $\bar{A}_{f_{CP}}$ and $A_{f_{CP}}$ are the decay amplitudes (for more information see [2]). For some decay modes $\mathrm{Im}(\lambda)$ is directly related to angles of the Unitarity Triangle. In particular for the decay $B^0 \to J/\psi K^0_S$ we can obtain the angle β, given by

$$\mathrm{Im}(\lambda) = \sin 2\beta. \tag{3}$$

2 The PEP-II storage ring

The PEP-II B Factory [3] is an asymmetric-energy e^+e^- collider which has a design luminosity of $3.0\,\mathrm{x}10^{33}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ and a centre-of-mass energy, $\sqrt{s} = 10.58$ GeV. This corresponds to the $\Upsilon(4S)$ resonance which lies just above the production threshold for B_d mesons and below that for B^* and B_s mesons. The cross-sections for $\Upsilon(4S)$ production and continuum $q\bar{q}$, are 1.05 nb and 3.39 nb respectively. The branching ratio of the $\Upsilon(4S)$ to $B\overline{B}$ meson pairs is close to 100% providing around $3\mathrm{x}10^7$ B meson pairs each year at design luminosity. The small mass difference between the Υ(4S) resonance and the two B mesons means that in the Υ(4S) rest frame the B mesons are almost at rest and travel only a short distance before decaying making their lifetimes hard to measure. To overcome this an asymmetric machine was built. This uses colliding beams of unequal energy to Lorentz boost the Υ(4S) in the direction of the beam axis. The beam energies chosen are 9 GeV for the electrons and 3.1 GeV for the positrons ($\beta\gamma = 0.56$). This results in the B mesons having appreciable velocities and measurable decay lengths ($\sim$260 μm). At the time of this conference the design luminosity had been achieved and surpassed (3.3×10^{33}). The design daily luminosity of 135 pb^{-1} per day was regularly achieved and exceeded with a maximum of 174.7 pb^{-1} achieved in one day.

3 BaBar detector

A complete description of the BaBar detector and its performance to date can be found in Ref. [4]. It consists of:

- a five layer double-sided silicon strip vertex tracker,
- a cylindrical drift chamber filled with Helium-Isobutane (80%-20%),
- a Čerenkov ring imaging particle identification system using 144 quartz bars,
- a Caesium Iodide (CsI) electromagnetic calorimeter with 6580 crystals,
- a superconducting solenoidal magnet (1.5 T),
- an instrumented flux return with 19 layers of resistive plate chambers for muon identification and K_L^0 reconstruction.

The tracking resolution can be parameterised by $\sigma_{p_t}/p_t = (0.13 \pm 0.01)\%.p_t + (0.45 \pm 0.03)\%$ [4], where p_t is in GeV/c. The silicon vertex tracker provides good vertex resolution with the z-resolution of the CP vertex typically being around 70 μm. Particle identification is achieved using a combination of measurements from all BaBar sub-detectors including the energy loss dE/dx in the drift chamber and in the silicon vertex tracker. Electrons and photons are identified in the calorimeter, and muons are identified in the instrumented flux return. The ring imaging Čerenkov detector provides excellent π-K discrimination above 750 MeV.

4 Branching fraction measurements for B decays to charmonium final states

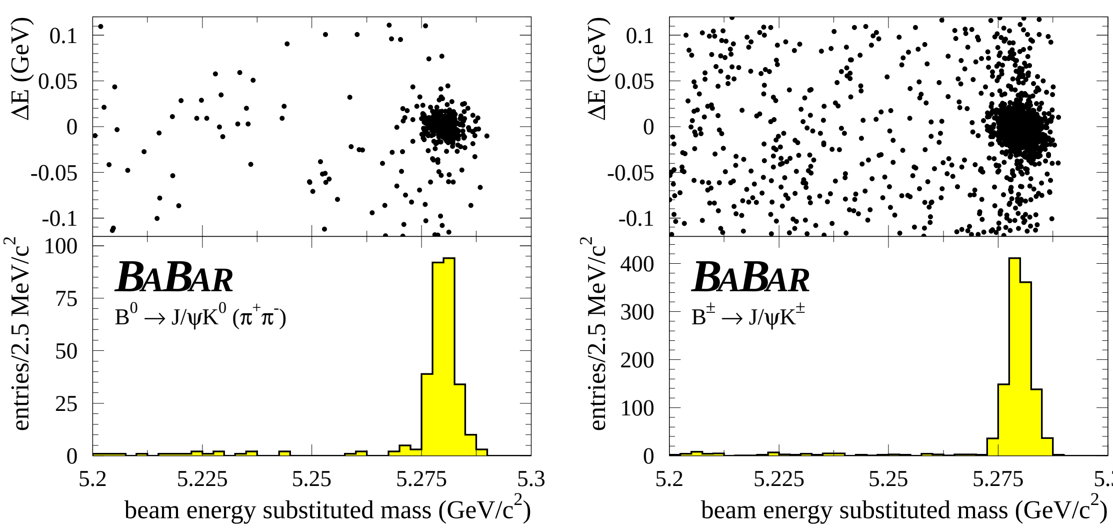

Figure 1: *Example distribution of the candidates in the ΔE–m_{ES} plane for $B^0 \rightarrow J/\psi\, K_S^0$ and $B^+ \rightarrow J/\psi\, K^+$.*

Exclusive B mesons are identified using a variety of kinematic cuts. To isolate the signal from background the variables ΔE, the difference between the reconstructed and expected B meson energy in the center-of mass frame, and m_{ES}, the beam energy substituted mass are used. These variables are defined as follows:

$$\Delta E = E_B^* - \frac{1}{2}\sqrt{s}, \tag{4}$$

$$m_{ES} = \sqrt{\left(\frac{1}{2}\sqrt{s}\right)^2 - P_B^{*\,2}}. \tag{5}$$

The resolution on ΔE is around 25 MeV and is dominated by detector resolution. The m_{ES} resolution is around 3 MeV and is dominated by the beam energy spread. Some example ΔE and m_{ES} distributions for two charmonium decays modes are shown in Fig. 1.

More detailed information on the measurement by BaBar of the branching fractions for B decays to charmonium final states can be found in [5]. In the determination of the branching fractions we have used the secondary branching fractions and their associated errors published by the Particle Data Group [6]. The branching fractions we have measured are shown in Table 1.

Table 1: *Branching ratios to $c\bar{c}$ final states.*

Decay	Branching Fraction (10^{-4})
$B^0 \to J/\psi\, K_S^0(\pi^+\pi^-)$	$8.5 \pm 0.5 \pm 0.6$
$B^0 \to J/\psi\, K_S^0(\pi^0\pi^0)$	$9.6 \pm 1.5 \pm 0.7$
$B^0 \to J/\psi\, K_L^0(\pi^+\pi^-)$	$6.8 \pm 0.8 \pm 0.8$
$B^0 \to J/\psi\, K^0(\mathrm{All})$	$8.3 \pm 0.4 \pm 0.5$
$B^0 \to J/\psi\, K^{*0}$	$12.4 \pm 0.5 \pm 0.9$
$B^0 \to J/\psi\, K^+$	$10.1 \pm 0.3 \pm 0.5$
$B^+ \to J/\psi\, K^{*+}$	$13.7 \pm 0.9 \pm 1.1$
$B^0 \to \chi_{c1} K^0$	$5.4 \pm 1.4 \pm 1.1$
$B^0 \to \chi_{c1} K^{*0}$	$4.8 \pm 1.4 \pm 0.9$
$B^0 \to \chi_{c1} K^+$	$7.5 \pm 0.8 \pm 0.8$
$B^0 \to \psi(2S) K^0$	$6.9 \pm 1.1 \pm 1.1$
$B^0 \to \psi(2S) K^+$	$6.4 \pm 0.5 \pm 0.8$
$B^0 \to J/\psi\, \pi^0$	$0.20 \pm 0.06 \pm 0.02$

5 B lifetime measurement

Using the 20.7 fb^{-1} of data from run 1 it was possible to reconstruct a very large number of charged and neutral B mesons. At the time of this conference we have 6967 ± 95 neutral candidates and 7266 ± 94 charged candidates. This is one of the largest datasets of fully reconstructed B mesons obtained to date. For complete information on the measurement of the lifetimes see [7]. The B^0 and $B^\pm$ lifetimes are extracted from a simultaneous maximum unbinned likelihood fit to the Δt distributions of the signal candidates where Δt is obtained from measuring the distance Δz between the decay vertices. To be able to perform this analysis it is vital to understand and parameterize

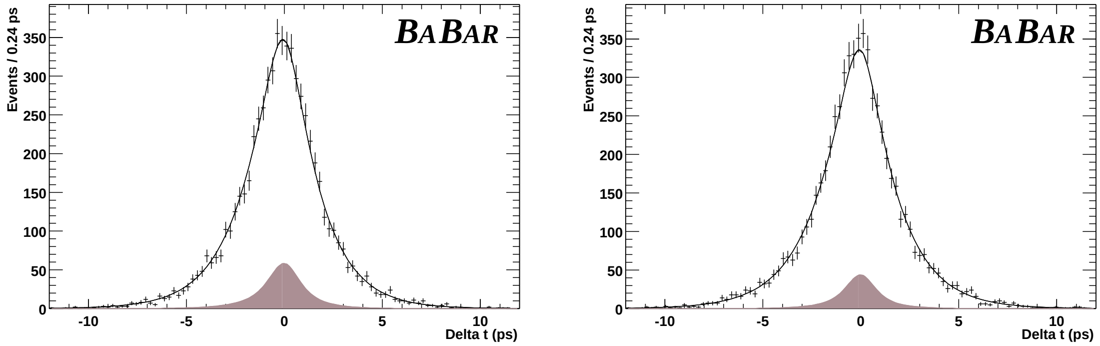

Figure 2: *Δt distributions for $B^0/\overline{B}^0$ (left) and B^+/B^- (right) candidates in the signal region ($m_{\rm ES}>5.27$ GeV/c^2). The result of the lifetime fit is superimposed. The background is shown by the hatched area.*

the detector vector resolution function because the RMS resolution for measuring Δt at *BABAR* is around 1.3 ps which is significant when compared to the lifetimes (1.5-1.6 ps). Studies with data and Monte Carlo simulation show that the resolution function for Δt is well modelled by the sum of a zero-mean Gaussian distribution and its convolution with a decay exponential shown in Eq. 6, where δ_t is the difference between the measured and true Δt values, and $\hat{a}$ represents the model parameters which are the fraction h of events in the core Gaussian component, a scale factor s to take account of the per-event errors σ, and a factor κ in the effective time constant of the exponential (for more information see [7]).

$$\begin{aligned} \mathcal{R}\left(\delta_t, \sigma | \hat{a} = \{h, s, k\}\right) &= h\frac{1}{\sqrt{2\pi}s\sigma}\exp\left(-\frac{\delta_t^2}{2s^2\sigma^2}\right) \\ &+ \int_{-\infty}^{0} \frac{1-h}{\kappa\sigma}\exp\left(\frac{\delta_t'}{\kappa\sigma}\right)\frac{1}{\sqrt{2\pi}s\sigma}\exp\left(-\frac{(\delta_t-\delta_t')^2}{2s^2\sigma^2}\right)\mathrm{d}(\delta_t'). \end{aligned} \tag{6}$$

Fig. 2 shows the Δt distributions with the result of the lifetime fit superimposed. The preliminary results for the B meson lifetimes are:

$$\begin{aligned} \tau_{B^0} &= 1.546 \pm 0.032\ (\text{stat}) \pm 0.022\ (\text{syst})\,\text{ps}, \\ \tau_{B^+} &= 1.673 \pm 0.032\ (\text{stat}) \pm 0.022\ (\text{syst})\,\text{ps}, \\ \tau_{B^+}/\tau_{B^0} &= 1.082 \pm 0.026\ (\text{stat}) \pm 0.011\ (\text{syst}). \end{aligned}$$

6 The $\sin 2\beta$ measurement

In e^+e^- storage rings operating at the $\Upsilon(4S)$ resonance the $B^0\overline{B}^0$ pairs produced in the $\Upsilon(4S)$ decays evolve in coherent P-wave states until one of the B mesons decays. If one of the B mesons (B_{tag}) can be ascertained to decay to a state of known flavor at a certain time t_{tag}, the other B (B_{CP}) is *at that time* known to be of the opposite flavor.

Each event which contains a CP candidate is assigned a B^0 or $\overline{B}^0$ tag if the rest of the event satisfies some tagging criteria. The most important parameter for tagging is the effective tagging quality $Q = \epsilon(1-2\omega)^2$, where ϵ is the tagging efficiency and ω is the probability of mis-tagging. The

statistical error on sin2β is inversely proportional to the square root of the tagging quality. The efficiencies and probabilities of mistag for the various types of tagging algorithm used are shown in Table 2. The algorithms are categorized in four different types:

- lepton tag where the flavour of the B meson is identified using the charge of a high momentum lepton from a semileptonic decay,
- kaon tag when the flavour of the B meson is identified from the charge of the kaon coming from the hadronisation of the s quark coming from the $b \to c \to s$ transitions,
- NT1 and NT2 tags chosen using the output of a neural network using correlated information such as secondary lepton charge, slow pions from D^* decays, and jet charge.

Table 2: *Mistag fractions measured from a maximum-likelihood fit to the time distribution for the fully-reconstructed B^0 sample. The uncertainties on ε and Q are statistical only.*

Category	ε (%)	w (%)	Q (%)
`Lepton`	10.9 ± 0.4	11.6 ± 2.0	6.4 ± 0.7
`Kaon`	36.5 ± 0.7	17.1 ± 1.3	15.8 ± 1.3
`NT1`	7.7 ± 0.4	21.2 ± 2.9	2.6 ± 0.5
`NT2`	13.7 ± 0.5	31.7 ± 2.6	1.8 ± 0.5
All	68.9 ± 1.0		26.7 ± 1.6

For the measurement of sin2β , B_{CP} is fully reconstructed in a CP eigenstate ($J/\psi\, K^0_S$, $\psi(2S)K^0_S$ or $J/\psi\, K^0_L$). By measuring the proper time interval $\Delta t = t_{CP} - t_{tag}$ from the B_{tag} decay time to the decay of the B_{CP} (t_{CP}), it is possible to determine the time evolution of the initially pure B^0 or $\overline{B}^0$ state:

$$f_{\pm}(\,\Delta t\,;\,\Gamma,\,\Delta m_d,\,\mathcal{D}\sin 2\beta) = \frac{1}{4}\,\Gamma\,\mathrm{e}^{-\Gamma|\Delta t|}\,[\,1\,\mp\,\mathcal{D}\eta_{CP}\sin 2\beta \times \sin \Delta m_d\,\Delta t\,]\,, \tag{7}$$

where the + or − sign indicates whether the B_{tag} is tagged as a B^0 or a $\overline{B}^0$, respectively. The dilution factor $\mathcal{D}$ is given by $\mathcal{D} = 1 - 2w$, where w is the mistag fraction, *i.e.*, the probability that the flavor of the tagging B is identified incorrectly. η_{CP} is the CP eigenstate of the final state and it is $\eta_{CP} = -1$ for the $J/\psi\, K^0_S$ and $\psi(2S)K^0_S$ modes, $\eta_{CP} = +1$ for the $J/\psi\, K^0_L$ mode. Although less pure, the $J/\psi\, K^0_L$ mode is very important because the oscillation is expected to be opposite to the other ones.

To account for the finite resolution of the detector, the time-dependent distributions $f_{\pm}$ for B^0 and $\overline{B}^0$ tagged events (Eq. 7) must be convoluted with the time resolution function mentioned earlier $\mathcal{R}(\Delta t; \hat{a})$:

$$\mathcal{F}_{\pm}(\,\Delta t\,;\,\Gamma,\,\Delta m_d,\,\mathcal{D}\eta_{CP}\sin 2\beta, \hat{a}\,) = f_{\pm}(\,\Delta t\,;\,\Gamma,\,\Delta m_d,\,\mathcal{D}\eta_{CP}\sin 2\beta\,) \otimes \mathcal{R}(\,\Delta t\,;\,\hat{a}\,), \tag{8}$$

Extraction of the amplitude of the CP asymmetry and the value of sin2β is done with an unbinned maximum likelihood fit. In order to extract as much information from the data itself and properly account for correlation, the fit is performed simultaneously to the CP and the flavor eigenstates. There are 35 parameters free in the fit. For the fit the B^0 lifetime and Δm_d are fixed to the currently best known values [6]. The Δt distributions for B^0 and $\overline{B}^0$ tags are shown in

Fig. 3. The results of the fit for sin2β using the full tagged data sample are shown below. More information and the latest results can be found in [8, 9].

$$\sin 2\beta = 0.34 \pm 0.20\,(\text{stat}) \pm 0.05\,(\text{syst}). \tag{9}$$

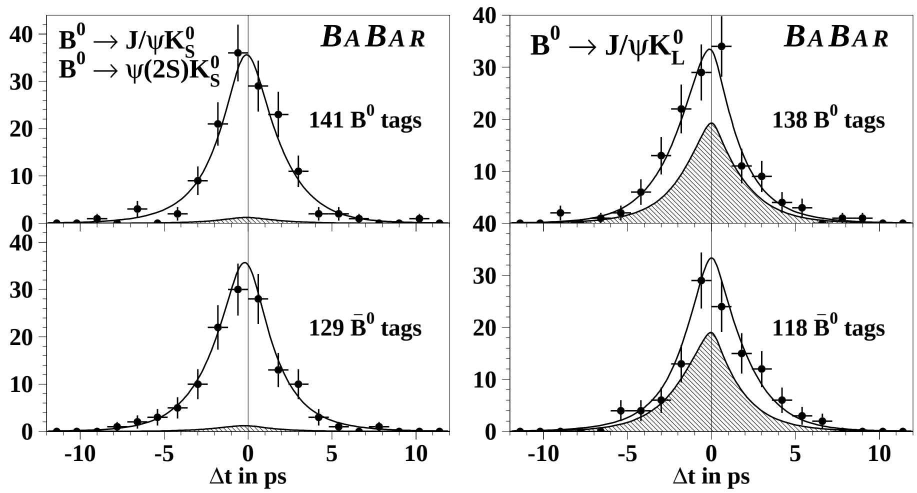

Figure 3: *Distribution of* Δt *for the* B^0 *and* $\overline{B}^0$ *tags. Shown on the left for* $B^0 \rightarrow J/\psi K^0$ *and* $B^0 \rightarrow \psi(2S)K^0_S$*, and on the right for* $B^0 \rightarrow J/\psi K^0_L$*. The background which is significantly larger for the* K^0_L *mode is shown by the hatched area.*

7 B mixing

The time dependent $B^0\overline{B}^0$ mixing measurement requires the determination of the flavour of both B mesons. Considering the $B^0\overline{B}^0$ system as a whole, one can classify the tagged events as *mixed* or *ummixed* depending upon whether the Bs are tagged with the same flavour or opposite flavour. From the time-dependent rate of mixed (N_{mix}) and unmixed (N_{unmix}) events, the mixing asymmetry $a(\Delta t) = (N_{unmix} - N_{mix})/(N_{unmix} + N_{mix})$ is calculated as a function of Δt and fitted to the expected cosine distribution. Fig. 4 shows the Δt and $a(\Delta t)$ distributions with the fit results superimposed.

We measure the $B^0\overline{B}^0$ oscillation frequency to be

$$\Delta m_d = 0.519 \pm 0.020\ (\text{stat}) \pm 0.016(\text{syst})\ \hbar \text{ps}^{-1}. \tag{10}$$

This result is consistent with previous measurements [6] and is of similar precision.

8 Conclusion

We have presented BaBar's measurement of the *CP* violating asymmetry parameter sin2β in the B meson system:

$$\sin 2\beta = 0.34 \pm 0.20\,(\text{stat}) \pm 0.05\,(\text{syst}). \tag{11}$$

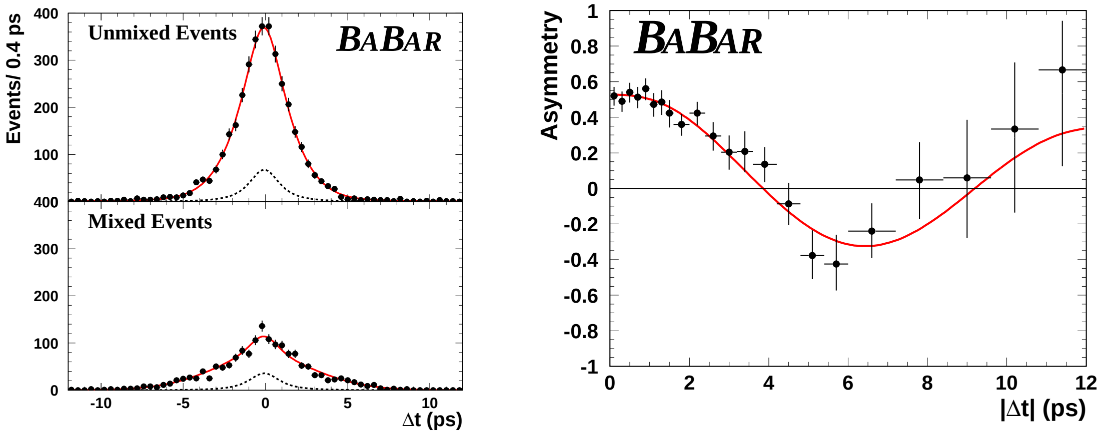

Figure 4: Δt *distribution for mixed and unmixed events (left) and the time-dependent asymmetry* $a(\Delta t)$ *between unmixed and mixed events (right).*

The measurement is consistent with the world average $\sin 2\beta = 0.9 \pm 0.4$ [6], and it is currently statistically limited by the size of the *CP* sample.

We have also presented measurements of various branching fractions for B decays to charmonium final states, B lifetime measurements, and time–dependent mixing which has been performed for the first time at the $\Upsilon(4S)$.

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